Policy Analysis

# Effect of Implementing Electronic Toll Collection in Reducing Highway Particulate Matter Pollution

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**ABSTRACT:** Highway vehicle emissions can result in adverse health problems to nearby residents and workers, especially during traffic congestion. In response, the policy to implement electronic toll collection (ETC) has helped alleviate traffic congestion, as compared to manual toll collection (MTC) and has led to reduced air pollution and improved public health. However, the effect of ETC in reducing particulate matter polluting the air is not well understood, especially in the ultrafine particle (UFP) range (particle diameter <100 nm). To the best of our knowledge, this is the first study to investigate how ETC affects the traffic pattern and air quality, especially UFP and $PM_{2.5}$. We selected a site in Tainan, Taiwan, and measured UFP and $PM_{2.5}$ concentrations before and after the construction of the ETC system. The computed traffic volumes during peak travel periods (7:00 AM to 9:00 AM and 4:00 PM to 6:00 PM) respectively, accounted for approximately 23−25% and 14−18% before and after the implementation of ETC, indicating that peak traffic volumes were more homogeneous after ETC. Moreover, the results indicate that the full implementation of ETC can help reduce UFP number concentrations and $PM_{2.5}$ mass concentrations in the highway downwind area by $4 \times 10^3$ #/$cm^3$ and 20.5 $\mu g/m^3$, respectively. After the full implementation of the ETC, significant reductions in both the UFP number concentration and $PM_{2.5}$ mass concentration were seen. Furthermore, excessive lifetime cancer risks (ELCR) from exposure to $PM_{2.5}$ and UFP together were reduced 49.3% after the implementation of the ETC. Accordingly, ETC not only helps alleviate traffic congestion but also reduces traffic emissions and lifetime cancer risk for people living or working near highways.
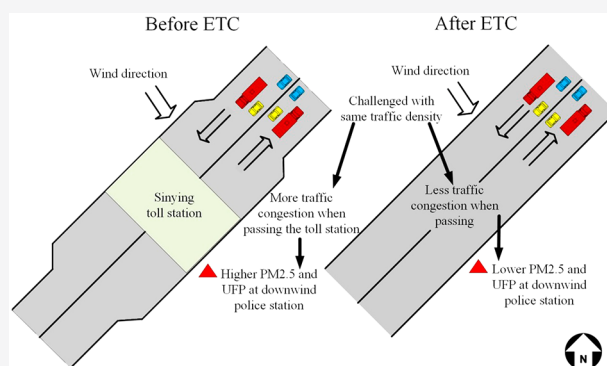
## INTRODUCTION

Highway pollution from traffic emissions is a serious environmental and health problem. Research has indicated that highway traffic emissions account for 37% of the $PM_{2.5}$ pollution in Taiwan.[1] As such, people living or working near busy roadways are exposed to higher concentrations of air pollution.[2−5] Because of the scarcity of land, a significant number of the population live close to a highway in Taiwan. In addition, there are around 2000 highway police patrolling the highways. Accordingly, these people are especially vulnerable to highway pollution.

Highway vehicle emissions such as UFPs and PM2.5 can result in adverse health effects. Both UFP and PM2.5 are associated with cardiovascular and respiratory diseases.[6,7] Children attending school near a highway experience increased rates of asthma and chronic respiratory problems.[8] One study indicated that near-roadway UFPs contain a high level of Ni and can cause a significant increase in bronchoalveolar lavage fluid (BALF) protein levels among test mice.[9] Another near-highway study from Boston (MA, USA) reported that long-

term UFP exposure was linked to cardiovascular diseases, diabetes, and hypertension.[10] Other research has shown that traffic police are especially vulnerable to respiratory diseases.[11−13] Studies from China have indicated that policemen exposed to daily traffic may suffer from cumulative DNA damage, resulting in a higher lifetime cancer rate.[14,15] In addition, traffic-related PM2.5 exposure can result in premature death from a study in Canada and China.[16,17] However, health effects of short-term exposure to traffic pollution still vary, with some studies indicating prominent respiratory symptoms[18] and others showing no evidence of adverse respiratory effects.[19]
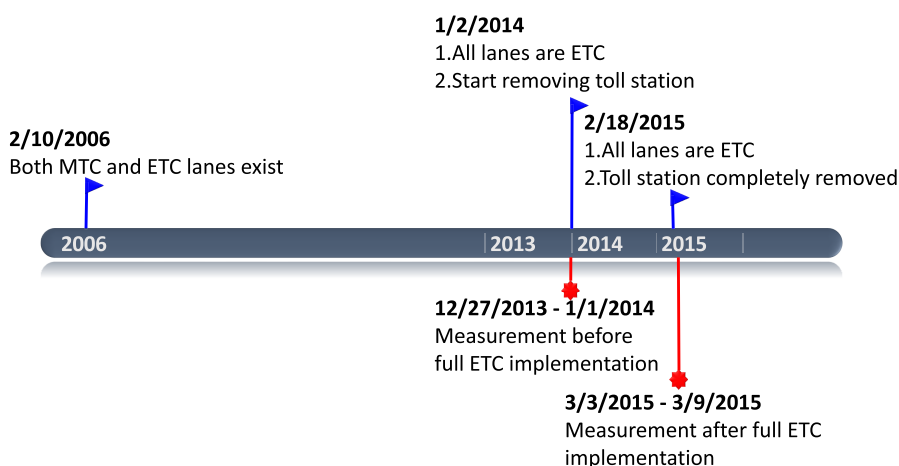
**Figure 1.** Timeline of the ETC construction.



**Figure 2.** Left panel is the Sinying toll station before ETC. Right panel is the highway after the implementation of the ETC; the ETC crosses over the highway as seen in the picture.

As an initiative meant to increase the traffic volume as well as reduce highway pollution, the ETC system was constructed on the two major north—south-bound highways in Taiwan on 2/10/2006. Figure 1 depicts the timeline of the ETC construction. Note that both the ETC and manual toll collection (MTC) coexisted from 2/10/2006 to 1/1/2014; however, during the transition process (before the full implementation of ETC), cars still had to slow down to 50 km/h and 0 km/h when passing though the ETC and MTC gate, respectively. The effect of toll stations on nearby air quality before the ETC system was installed can be seen in our previous research.[20] The ETC has an advantage over the MTC since it allows vehicles to move continuously without stopping. Note that the transaction times for the ETC and MTC are 2.06 and 7.72 s, respectively.[21] Therefore, the ETC accelerates traffic flow and reduces the traffic congestion at the toll station, thus reducing the amount of nearby air pollution from vehicle emissions. Similar results were seen when London implemented the congestion charging scheme to relieve the traffic congestion.[22] Moreover, ETC is contact free which can help reduce the transmission of infectious diseases such as COVID-19 that can transfer through close contact and other viral-mechanisms.[23,24] After the full implementation of the ETC system on 1/2/2014, vehicles on two main north and southbound highways (Highway 1 and Highway 3) in Taiwan no longer needed to reduce their speed or stop at the toll stations; this can further reduce vehicle emission on highways. The total length of the ETC highway is 926 km, one of the longest in the world. Through the use of wireless communications technology, vehicles equipped with eTAG can be electronically identified and tolled while passing through a toll gate. For those not using eTAG, the ETC system can also track license plates and mail the bill to the car owner. The ETC system in Taiwan also ensures fairness since it applies mileage charge rates; that is, road users are charged based on the distances they travel on a highway. In addition to collecting tolls, the ETC can also collect traffic related data, such as vehicle counts by type, travel speed, and the number of vehicles carrying eTAGs.

A study from Lisbon, Portugal, showed that CO concentration can be reduced 61−80% with the implementation of ETC.[25] Studies have indicated that during vehicle acceleration and deceleration, large amounts of air pollution are emitted.[26,27] Although it has been reported that the construction, operation, and maintenance cost of an ETC system is higher than that of MTC, the improvement in air quality and public health using ETC cannot be overlooked. Most of the previous studies having focused on the effect of

ETC in reducing gaseous air pollution, very few studies have focused on the effect of ETC in reducing particulate matter, especially $PM_{2.5}$ and UFPs. Moreover, reduction of excessive lifetime cancer risk (ELCR) from particulate exposure associated with the implementation of ETC has not been clearly evaluated.

In this study, we aim to investigate the effect of an ETC system on reducing downwind air pollution (i.e., wind that is $\pm45°$ perpendicular to the highway) and when the wind speed is greater than or equal to 0.5 m/s at the Sinyin toll station, located in Tainan, Taiwan. We also investigated the ELCR associated with the people near highway environments.

### ■ MATERIALS AND METHODS

**Site Description.** The research site was located at the Sinyin toll station, Tainan, Taiwan. At the site, two sampling stations were set up. One was located at the downwind (police station (23.357948 latitude, 120.339121 longitude) of the highway, while the other was located at the upwind station (reference station, 23.360140 latitude, 120.339510 longitude). The reference station was installed inside a Hyundai Grand Starex Van, and the instruments were powered by batteries (model 60038, Delkor, Johnson Controls Inc., USA). We obtained the meteorological data from Taiwan Central Weather Bureau's Madou Station (23.10599 N latitude, 120.14551 E longitude), located 21.5 km southwest of the Sinyin toll station. The meteorology site was located on top of the fifth floor of the Tainan Second Fire Department, approximately 28 m above ground. During the first campaign (12/27/2013−1/1/2014), before the full implementation of the ETC, the Sinyin toll station included both MTC and ETC, as seen in Figure 2. Notice that at the Sinyin toll station, the highway expanded from three to seven lanes on both northbound and southbound directions to help reduce the wait time. There were four MTC and three ETC lanes for both the northbound and southbound routes. The construction work for transitioning to full ETC occurred from 1/2014−10/2014, which reduced both northbound and southbound lanes back to three lanes and eliminated the Sinyin toll station. We conducted the second campaign after the full implementation of the ETC from 3/3/2015 to 3/9/2015, at which time, all lanes of the highway used ETC.

**Instrumental Setup.** Details of the instrument setup in the first campaign (before full implementation of ETC) can be seen in our previous study.[20] In the second campaign (after full implementation of ETC), we used a scanning mobility particle sizer (SMPS, DMA Model 3081 and CPC model 3787, TSI Inc., Shoreview, MN, USA) to measure the particle number concentration and size distribution of particles from 8 to 224 nm with a scan time of 150 s (90 upscan/30 downscan/30 retrace). We used particles smaller than 100 nm for UFP concentration. For $PM_{2.5}$ measurement, we used a DustTrak (model 8520, TSI Inc., Shoreview, MN, USA) monitor with 60 s resolution time. An ambient fine particulate sampler (model PQ200, Mesa Laboratories, Inc., Butler, NJ, USA) located 3 m from the DustTrak was also used to sample the upwind concentration during the campaign. We then corrected the DustTrak measurements to the PQ200 reading. Lastly, we averaged both SMPS and DustTrak to 5 min intervals. The wind from the highway consists of around 90% and 57% of the total measurement data before and after the full implementation of the ETC, respectively. We used the reference station data as the background concentration; therefore, the back-

ground concentration and upwind concentration were obtained simultaneously. We then subtracted the background concentration from the downwind police station measurement for each data points.

**Instrumental Intercomparison and QA/QC.** During both campaigns, we performed side by side instrumental comparisons of the two stations by driving the van from the reference station to the downwind police station. The intercomparison was performed every other day for at least 1 h to synchronize the two stations. In addition, we put a HEPA filter (Pall Corporation, New York, NY, USA) in the sampling inlet to ensure there were no leaks in the sampling line before and after every instrumental intercomparison.

**Excessive Lifetime Cancer Risk (ELCR) Reduction from ETC.** The ELCR from particle exposure can be described by[28]

$$ELCR = \frac{SF_{PM2.5} \times Q}{BW} \int_{d_p} C_{PM2.5}(d_p)\beta_{PM2.5}(d_p) \, dd_p$$
$$+ \frac{SF_{UFP} \times Q \times C_F}{BW} \int_{d_p} C_{UFP}(d_p)\beta_{UFP}(d_p) \, dd_p \tag{1}$$

where $SF_{PM2.5}$ and $SF_{UFP}$ is the $PM_{2.5}$ and the UFP inhalation slope factor given as $1.57 \times 10^{-5}$ kg day/mg and $4.58 \times 10^{-4}$ kg day/mg, respectively.[29,30] BW is body weight (assumed as 70 kg), and $Q$ is the human daily inhalation rate given as 20 $m^3$/day. In addition, $C_F$ is the conversion coefficient ($6.60 \times 10^{-13}$ $mg/nm^2$)[28] that converts the UFP surface area into mass concentration. $C_{PM2.5}$ is the $PM_{2.5}$ mass concentration ($\mu g/m^3$), and $C_{UFP}$ is the surface area concentration ($nm^2/m^3$) of the UFPs. Furthermore, $\beta_{PM2.5}$ is the respiratory mass deposition fraction for $PM_{2.5}$, which was assumed to be 0.23 since the size distribution of coarse particles was not available.[31] $\beta_{UFP}$ is the respiratory deposition fraction for UFPs, which is dependent on particle size.[32]

### ■ RESULTS AND DISCUSSION

In this section, we first discuss the effect of ETC on traffic patterns as well as diurnal patterns of $PM_{2.5}$, UFP, and traffic. Then, we describe how the full implementation of ETC reduces air pollutants (i.e., $PM_{2.5}$ and UFP) in the surrounding environment. Finally, we examine the reduction of ELCR from the implementation of ETC.

**Effect of ETC on Traffic Patterns.** To evaluate the impact of ETC implementation on the traffic patterns of National Highway No. 1 in Taiwan, we compared the data collected before and after the introduction of the ETC system. The data were collected via the vehicle detectors (VDs) and ETC system located on the Sinyin section of National Highway No. 1. The time intervals analyzed were the same as the air pollution monitoring. We computed the traffic volume during peak hours (7 AM to 9 AM and 4 PM to 6 PM) and found that peak-hour traffic accounted for approximately 23−25% and 14−18% of the total traffic volume before and after the implementation. These results indicated that this highway section was less crowded and that the peak traffic was spread more evenly than before. Moreover, the average speed increased by 2.67% (increased from 98.7 km/h to 101.4 km/h) after the implementation of ETC. By taking the distance (6 km) between the current detectors and the original Sinyin manual toll collection plaza as an example, it was found that the 2.67% speed increase corresponded to a savings of 0.081 min of average travel time. For the days we collected the traffic

data, the average number of vehicles passing that station is 280,548.15 per day, resulting in a total travel time of 16,552.34 h per day on average. Therefore, the 378.74 h saved corresponds to 2.29% of the total travel time saved in this 6 km distance.

**Diurnal Profile.** Figure 3 shows the diurnal pattern of the traffic as well as the background-subtracted $PM_{2.5}$ and UFP
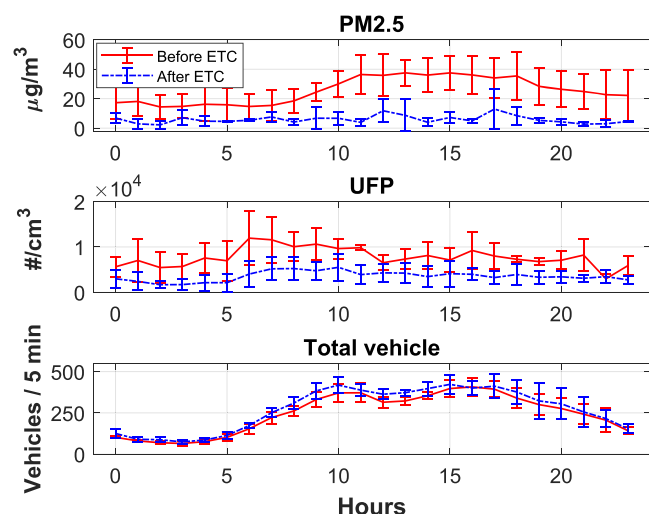


**Figure 3.** Diurnal profiles of the $PM_{2.5}$, UFP, and total vehicle concentrations measured at the police station before and after the implementation of the ETC. The error bars indicate one standard deviation.

concentration before and after the implementation of the ETC. Both show that $PM_{2.5}$ and UFP concentrations after the implementation ETC were mostly significantly lower ($p <$ 0.05), while the traffic volume diurnal profile remained similar, except that the peak traffic volume was more spread out. Notice that the daytime and nighttime variations were also smaller after the implementation of ETC. Figure 3 also indicates that traffic volume had a lesser impact on $PM_{2.5}$ and UFP concentrations after the implementation of ETC. Moreover, traffic emissions are the major contributor to UFP concentrations in this study, and our data show that the ETC system not only helped reduce traffic congestion, but also reduced traffic emissions.

**Effect of ETC on Reducing Air Pollution.** Table 1 is a descriptive statistical table of the $PM_{2.5}$ mass concentration and UFP number concentration at the measurement site. The challenged traffic volume and wind speeds were similar during the two campaigns. Although we saw a slightly higher traffic

volume during the campaign after the full implementation of ETC, the reduction in $PM_{2.5}$ and UFPs remained significant ($p < 0.05$).

Figure 4 shows the background-subtracted SMPS size distribution profile from the highway. Notice the significant
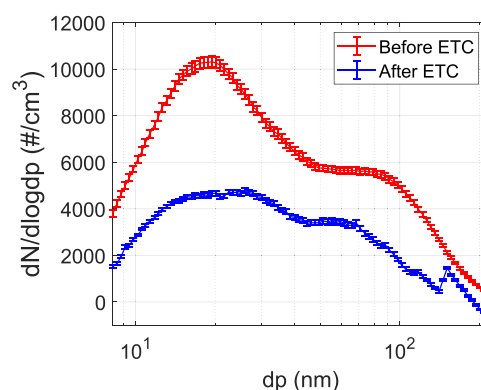


**Figure 4.** Background-subtracted SMPS size distribution and particle number concentration before and after the implementation of ETC. The error bars represent one standard error.

reduction in the peak around 15−30 nm. This peak is likely to originate from vehicle emissions, which generally have a median diameter of around 20 nm.[33,34] The reduction in particle number concentration at different sizes of UFP can be seen, further demonstrating that the ETC system helps reduce air pollution. However, in the after ETC curve, a peak can be seen in $d_p \approx 150$ nm, and in particular less reduction can also be seen for $d_p$ greater than this particle size. Since vehicle emissions generally have a median diameter of around 20 nm, the above results suggest these UFP concentrations could be considered as the background concentration rather than vehicle emissions.

After the full implementation of the ETC, we further compared the background-subtracted $PM_{2.5}$ and UFP concentrations under different traffic volumes, as shown in Figure 5. Results indicate that full utilization of the ETC significantly reduced $PM_{2.5}$ and UFP concentrations ($p < 0.01$) under different traffic volumes.

**ELCR Reduction after ETC.** Table 2 list the PM2.5 and UFP concentrations from the highway before and after the full implementation of the ETC. Notice that both the PM2.5 mass concentration and UFP number concentration were reduced by 20.5 $\mu g/m^3$ and $4 \times 10^3$ #/$cm^3$, respectively. The above reduction in ELCR from calculating PM2.5 and UFP alone was 78.7% and 48.8%, respectively. The total ELCR reduction considering both PM2.5 and UFP together was 49.3%. The

**Table 1. Statistical Descriptions of $PM_{2.5}$ (Background-Subtracted), UFP (Background-Subtracted), Traffic Volume, and Wind Speed (WS) Obtained from the Police Station (PS) before and after the Full Implementation of the ETC**

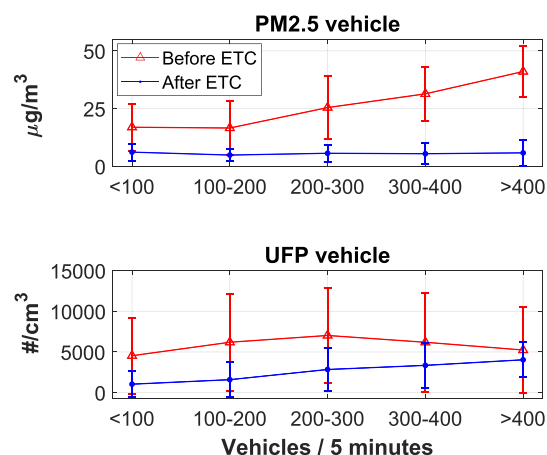| | $PM_{2.5}$ ($\mu g/m^3$) | | UFP (#/$cm^3$) | | Traffic (vehicles/5 min) | | WS (m/s) | |
|---|---|---|---|---|---|---|---|---|
| | before | after | before | after | before | after | before | after |
| min. | 0.1 | 0.0 | $1.2 \times 10^2$ | $6.2 \times 10^1$ | 29 | 53 | 0.7 | 0.6 |
| first qu. | 14.7 | 3.3 | $4.2 \times 10^3$ | $2.1 \times 10^3$ | 110 | 149 | 1.4 | 1.9 |
| median | 25.1 | 4.9 | $6.8 \times 10^3$ | $3.7 \times 10^3$ | 269 | 292 | 1.9 | 2.4 |
| mean | 26.0 | 5.5 | $7.9 \times 10^3$ | $3.9 \times 10^3$ | 249 | 272 | 2.1 | 2.3 |
| third qu. | 35.7 | 6.7 | $1.0 \times 10^4$ | $5.3 \times 10^3$ | 352 | 375 | 2.6 | 2.6 |
| max. | 85.2 | 33.5 | $4.2 \times 10^4$ | $1.1 \times 10^4$ | 535 | 658 | 5.1 | 3.3 |
| std | 14.3 | 3.5 | $5.3 \times 10^3$ | $2.2 \times 10^3$ | 129 | 130 | 1.0 | 0.5 |

**Figure 5.** Background-subtracted PM$_{2.5}$ and UFP concentrations under different traffic volumes before and after the full implementation of the ETC system. The error bars above correspond to one standard deviation.

**Table 2. PM$_{2.5}$ and UFP Concentration from the Highway (Background-Subtracted) That Was Used to Calculate the ELCR at the Police Station**

|                    | PM$_{2.5}$ ($\mu$g/m$^3$) | UFP (#/cm$^3$)        | total ELCR           |
| ------------------ | ------------------------- | --------------------- | -------------------- |
| before             | 26.0                      | $7.9 \times 10^3$     |                      |
| after              | 5.5                       | $3.9 \times 10^3$     |                      |
| differences        | 20.5                      | $4.0 \times 10^3$     |                      |
| ELCR before        | $2.7 \times 10^{-5}$      | $1.5 \times 10^{-3}$  | $1.5 \times 10^{-3}$ |
| ELCR after         | $5.7 \times 10^{-6}$      | $7.5 \times 10^{-4}$  | $7.5 \times 10^{-4}$ |
| ELCR reduction (%) | 78.7                      | 48.8                  | 49.3                 |

ELCR risk from UFP is 54 and 131 times higher than that from PM2.5, before and after the ETC, respectively. The emission standards remain identical before and after the full implementation of ETC. As to the traffic constitution, it is impacted by land use and demography,[35] which may not drastically change during the short period of time we collected the data. Although the traffic constitution cannot be fully identical, we believe that the reduction is primarily contributed by the implementation of ETC. Similar results are reported by the Freeway Bureau, Ministry of Transportation and Communications in Taiwan. Other studies have also shown similar patterns, indicating that UFP number concentration contributes more to the ELCR than PM$_{2.5}$.[36−38] Therefore, it is more effective to control UFPs than PM$_{2.5}$ in terms of reducing ELCR.

## CONCLUSIONS

The full implementation of the ETC can significantly reduce PM$_{2.5}$ mass concentration and UFP number concentration when challenged with similar traffic volumes. The traffic volume, PM$_{2.5}$ concentration, and UFP concentration were also more homogeneous after the introduction of ETC. Furthermore, the ELCR can be reduced almost 50% after the full implementation of the ETC. The decrease in the ELCR value mostly resulted from the reduction in UFP concentration rather than PM$_{2.5}$. Thus, reducing UFPs may be more beneficial than reducing PM$_{2.5}$ in near-highway environments in terms of reducing the ELCR. It should be noted that this study is limited to one site in Taiwan; consequently, more studies are needed to evaluate how different policy measures,

such as ETC, help reduce the PM$_{2.5}$ and UFP concentrations in near-highway environments. Another limitation is that the main PM fraction typically affected by the traffic is the coarse fraction (PM2.5−10) due to resuspension.[17] However, we did not have the coarse particle instruments in our study. Finally, this study can serve as a guide for future highway toll collection planning and air quality management.

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### Notes

The authors declare no competing financial interest.

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## ■ NOTE ADDED AFTER ASAP PUBLICATION

This paper was published ASAP on July 17, 2020, with errors in the Abstract and the Introduction. The corrected version was reposted on July 20, 2020.